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Abstract. Based on measurements at the Heidelberg heavy-ion storage ring TSR, we present lifetimes of all six 3p and 3d levels of Fe XII that are long lived, because they do not have E1 decay channels. We discuss the corresponding term analysis and the Fe XII spectral lines that should be useful for the diagnostics of low density plasmas.

1. Introduction

Edlén's identification of prominent visible light corona lines with electric-dipole forbidden transitions in the ground configurations of highly charged ions [1] forced a revolution in the hypotheses about the solar environment. Such lines have since been observed in a wide variety of astrophysical objects. Knowing the transition probabilities of the E1-forbidden transitions, be they magnetic dipole (M1), electric quadrupole (E2), magnetic quadrupole (M2), or even higher multipole order transitions, helps to interpret emission and absorption features and to quantify the environmental parameters of the emitter or absorber plasma. However, not all of these lines are prominent; in a spectrum like that of the solar corona, ions of many elements are present, and line blends are frequent, so that line identification remains a major problem. In spite of many attempts at providing full wavelength coverage by sounding rockets and satellites and ever improving calculational efforts towards a complete analysis, the phrase " ... about half of the observed lines remain unidentified" has been a recurring theme.

One of the reasons for this problem is that when the first observations were made, the laboratory data base was much poorer than what is available now. In a number of cases it may well have happened that line identifications proceeded by wavelength coincidence, possibly assigning some of the lines to the wrong elements and charge states and not always recognizing blends. Next, many lines are not excited in the laboratory (requiring much lower density in order to escape quenching collisions), or have never been thought to be worth pursuing on Earth. In order to remedy this situation, several data bases (CHIANTI [2, 3], MEKAL [4], and others) have been developed that provide reasonably complete spectra based on calculations and observations. Any such database ultimately relies on original measurements. For the Fe spectra in the soft-x-ray and EUV ranges, where the *Chandra* and $XMM-Newton$ spacecrafts detected hundreds of lines, such observations have been provided largely by electron beam ion trap work by Beiersdorfer, Brown, Lepson *et al* [5, 6]).

A great challenge now is a critical reevaluation of the data in such data bases, checking the entries for completeness as well as correctness, for validity (element, charge state, abundance, excitation condition). This is tedious work, combining detailed and large scale calculations with data base analysis. One of us (GDZ), in collaboration with Helen Mason (Univ. of Cambridge, UK) and Pete Storey (UCL, UK) has taken a particular interest in the Fe ions in the corona, and several critical reevaluations have recently been published [7, 8]. In order to support the correct modeling effort of the full spectrum so that the latter can be properly compared to solar and terrestrial data, we have addressed the E1-forbidden decay rates of 3p and 3d levels in Fe XII.

2. Literature data on Fe XII

The P-like ion Fe^{11+} (spectrum Fe XII) has a $3s^23p^3$ ground configuration that harbours five levels, the true ground level $^4S^o_{3/2}$ as well as the levels $^2D^o_{3/2,5/2}$ and $^2P^o_{1/2,3/2}$. There also are eight displaced levels ($3s3p^4$) and 31 $3s^23p^23d$ levels (see figure 1). Until rather recently, many of the 3d levels were not known from experiment (see [9, 10] and the NIST on-line data base that heavily relies on these tabulations), although by and by some identifications have been added [11, 12]. The relatively few transitions - all of them E1-forbidden - in the ground configuration have wavelengths in the range from the ultraviolet (UV) (about 357 nm) to the vacuum UV (124 nm). An atomic system with such a ground configuration should be useful for plasma temperature diagnostics [13, 14, 15]. A fair number of calculations have dealt with the transitions in the ground configuration [16, 17, 18, 19, 20, 21, 22, 23] (and possibly others). Very few attempts have been made to describe more than the ground configuration, and among those few, not all have included E1-forbidden transitions (see, for example, [24]). The 3d levels of highest total angular momentum (in this case, J=9/2) can decay only by M1 and E2 transitions (figure 1); the transitions lie in the IR, in the UV and in the EUV; the level lifetimes reach several milliseconds. The many other 3d levels mostly decay to the ground configuration by transitions in the EUV and have level lifetimes in the picosecond and nanosecond ranges.

Facing such a multitude of individually mostly weak lines, spectral analysis is struggling. It might seem advantageous if a level decay is not spread out over many competing branches. For example, the $3s^23p^23d$ levels of total angular momentum J=7/2 have single decay channels to the ground configuration, but single lines are notoriously difficult to assign. This problem has been addressed in beam-foil spectroscopy, exploiting the prediction that these J=7/2 levels are relatively long lived, which in beam-foil work means nanosecond lifetimes. Indeed, delayed spectra of foil-excited ion beams have served to identify three levels ($3s^23p^23d$ $^{2,4}F_{7/2}$, $^2G_{7/2}$) and their decays in Fe XII [12], and some similar cases in other ions.

Del Zanna *et al* have recently revisited and reanalyzed the solar spectra of Fe X and Fe XII [7, 8] on the basis of extensive calculations, including scattering calculations (for line intensities) and semi-empirically adjusted atomic structure calculations, as well as reviewed all line identifications using laboratory and astrophysical spectra, and they now have identified most of the 3d levels. In the process, practically all scattering calculations preceding [25] were found to be lacking. In a complementary approach, experiments were undertaken at the Heidelberg heavy-ion storage ring TSR in order to test specific aspects of the same atomic structure calculations as are used for the spectral analysis. The experiments targeted the transition probabilities in terms of level lifetimes, namely those long-lived levels that by virtue of their longevity depend in their population possibly strongly on the density in the emitting plasma. Such data should help determine the validity of certain key entries to collisional-radiative models.

3. TSR experiment and results

The technique of passive optical measurements of atomic lifetimes at an ion storage ring is an extension of the beam-foil technique. A fast ion beam (typical velocity of 2 cm/ns, or 6% of the speed of light) is produced in an accelerator and sent through a gas or a foil where in collisions with the target medium the fast ion beam reaches a new charge state distribution and many of the ions are excited. The ions are sorted by their charge state, and only one ion species (one mass number, one velocity, one charge state) is selected and guided to the ion storage ring, which takes about 5 μs. The ion beam is fed into the storage ring, a loop of a well evacuated beam tube (ultrahigh vacuum of $p \approx 10^{-11}$ mbar) in which the ion beam is guided by magnetic dipole and quadrupole fields. The ion beam is being accumulated over about 30 turns in the 55 m circumference storage ring; then the feeding stops and the ions are left coasting, in our case for 200 ms to 2 s. The ion beam current is monitored by a beam profile monitor, which consists of sets of microchannel plates that detect the slow ions produced by collisions of the circulating fast ions with the atoms and molecules of the residual gas. For the optical observation of atomic decays, either a photomultiplier outside the vacuum vessel [26, 27] or open photomultipliers (channeltrons) inside the ring vacuum [28] detect the emitted light (figure 2). In the UV and visible spectral ranges, filters can narrow the band pass, and the actual signal is then almost exclusively from the decay of interest. In the EUV, no filtering is available, and the channeltron then sees light also from the excitation of the residual gas or from its later recombination on the walls of the vacuum vessel. The slope of the exponential decay curve yields the decay rate and its inverse, the level lifetime. However, the apparent decay rate contains a contribution from ion loss (the ion storage time constant), which has to be corrected for as well as for relativistic time dilation. Both effects partly cancel each other; the sum is a correction that usually is well below 1%.

For the studies of Fe XII, three different detectors were needed. For the decay of the $3s^23p^3$ $^2P^o$ level at 310 nm, a bialkali photomultiplier (EMR 541N) was combined with an interference filter [29]. For the $3s^23p^3$ $^2D^o$ level decays (217 nm / 241 nm) a solar blind photomultiplier of exceptionally low dark rate (EMR 541Q) was employed without a filter; the decay curves (see [29]) showed a third, faster component which may originate from decay branches (at about 270 nm and 180 nm, respectively [23]) of the $3s^23p^3$ $^2P^o$ levels as well as from the $3s^23p^23d$ $^2G_{9/2}$ level decay [29].

The same level and its companion level $^4F_{9/2}$ have EUV decay branches, and these decays reach short-lived levels which in turn decay to the ground configuration levels. The decay curves of the latter contain as cascades and therefore with the original time constants also the 3d $^4F_{9/2}$ and 3d $^2G_{9/2}$ level decays. In face of the disadvantage that there is no narrowband filter of high transmission in the EUV, there is the advantage that the same detector sees practically all EUV decays at the same time, and thus also all decays that have the same slow decay components (that supposedly relate to only two levels). Also, it was not necessary to determine accurate wavelengths before doing these lifetime measurements. The earlier measurements in the far UV had already indicated the 4 ms lifetime of one of the 3d levels. This older finding helped to disentangle the superposition of the EUV decays in our most recent experiments (figure 3), the analysis of which yielded level lifetimes of 4 ± 1 ms and 11 ± 1 ms, respectively. The uncertainties of the results are relatively large (25% and about 10% percent, respectively), because the decays are observed on top of the ion beam related EUV signal, which dominates the statistical reliability with which the shorter lived decays can be evaluated. Moreover, the two lifetimes are too close to each other to be obtained from a multiexponential fit with a high reliability. Adding to the fitting difficulties is the observation that the amplitude of the faster component is much smaller than expected if the initial population of the J=9/2 levels was equal and all decays were detected. Yet another problem is the appearance of a superimposed small amplitude oscillation on the signal. Such oscillations have been seen in various experiments at the heavy-ion storage ring, but beyond a hypothesis that they relate to ion beam dynamics, no explanation or quantification has been possible yet. The oscillation was included in the fit and improved the *chi-squared* value. The results for the 3d level lifetimes are listed in table 1. This table also lists the wavelengths of the dominant decay channels of the two long-lived J=9/2 levels as given by Del Zanna *et al* [8] on the basis of experimental data; these differ quantitatively from the values predicted by Biémont *et al* [23] on the basis of more general calculations.

4. Discussion

Biémont *et al* [23] and Del Zanna *et al* [8] make predictions of the principal decay channels of the two 3d J=9/2 levels (see figure 1). We adopt the latter, because they involve adjustments to observation. In the EUV range, the strongest of the decay branches of the 3d $^4F_{9/2}$ level are expected near 59 nm (E2 decay to 3s3p^4 $^4P_{5/2}$) and 25.2 nm (M2 transition to s^{2}3p^3 $^2D^o_{5/2}$). The strongest decay channels of the 3s^{2}3p^2(^{1}D)3d $^2G_{9/2}$ level according to Del Zanna *et al* are an M1 transition (at 185 nm) to 3s^{2}3p^2(^{3}P)3d $^4F_{9/2}$, another M1 decay (at 163 nm) to 3s^{2}3p^2(^{1}D)3d $^2F_{7/2}$, an M2 transition (at 22.17 nm) to 3s^{2}3p^3 $^2D_{5/2}$, and an E2 decay (at 64.3 nm) to 3s3p^4 $^2D_{5/2}$. The J=5/2 excited levels in turn preferentially feed the two J=5/2 levels of the ground configuration, giving rise to the 33.8 nm and 36.4 nm lines. The 3s^{2}3p^3 $^2D^o_{5/2}$ level with its about 300 ms lifetime is boosted in population by these growing-in (faster) cascades, but the actual measurement of the long level lifetime is hardly affected. If the 3d level cascades would reach the $^2D^o_{3/2}$ level with its 18-ms lifetime that is so much closer to that of the two 3d levels, the evaluation of the $^2D^o_{3/2}$ level would be seriously hampered - if the upper level population was comparable in magnitude. Similarly, the measurement of the shorter lifetimes of the 3s^{2}3p^3 $^2P^o_{1/2,3/2}$ levels would suffer from the presence of cascades that are rather close in lifetime and thus would seriously impede the decay curve analysis - but the branchings channel very little of the slow 3d cascades, if any, to these two levels. The ease of fitting the UV decay curves and the rather weaker (though not calibrated) appearance of the EUV decay curves suggest that the long-lived 3d levels are less populated than the heavily cascade-fed long-lived levels in the ground configuration, so that the perturbation of the ground configuration level decay curves by the slow cascades is minor.

The measurement accuracy of the ground configuration level lifetimes is much better than the scatter of the predictions (see table 1 and [29]), which is particulary bad for the $^2D^o_{5/2}$ level. Only very few of the predictions (for example, [23, 8]) match all measured lifetimes at the same time, which should be a strong indicator of quality. In order to provide a 'second opinion', although by employing the same measurement technique, the 3s^{2}3p^3 level lifetimes have also been measured in Co XIII, the neighbouring element. Fewer calculations have treated Co than have been applied to Fe, but the intercomparison is very instructive (for a graphical presentation, see [30, 31]). At a distance from these two elements, and measured by a very different technique that employs an electron beam ion trap, the $^2D^o_{5/2}$ level lifetime in Kr XXII [32] provides another experimental reference. The various predicted level lifetimes scatter by up to 70% around the experimental results. For most of the calculations of P-like ions and our three sample ions along the isoelectronic sequence, at best one or two individual values happen to be close to experiment, and the predicted isoelectronic trend is not bourne out by experiment. Overall, the calculations by Biémont *et al* [23] appear to represent the state of the art along the isoelectronic sequence. Of course, it would be good to extend the measurements to more elements, say to Mn and Ni, in order to check the experimental findings for Fe, the solar corona element of foremost interest.

The above lifetime measurements at TSR have been performed with very little wavelength discrimination, relying on an experimental arrangement that provided ions of a single isotope and charge state, so that only a few long-lived levels were expected to contribute to any decay curve that should reflect millisecond lifetimes. Del Zanna and Mason [8], aided by electron excitation calculations done by Storey *et al* [25], identified one of the 3d J=9/2 level decays with a bright coronal line observed at 59.26 nm [8]. This line is the brighter one of the two, since it represents the majority decay branch (more than 50%) of its upper level, 3d $^4F_{9/2}$. The other line, predicted near 64.3 nm, is expected to represent only about 15% of the total decay of the 3d $^2G_{9/2}$ level. There is no clear candidate line for this decay, with its wavelength at the edge of the range covered by the SUMER instrument on the SOHO spacecraft. Given the many-millisecond lifetime, it cannot be seen in beam-foil spectra (where there are many unassigned lines), but it may some day be seen in an electron beam ion trap, which can produce spectra that are dominated by a single element. Once the wavelength can be specified to a higher accuracy, the line will likely be recognized in solar spectra, too.

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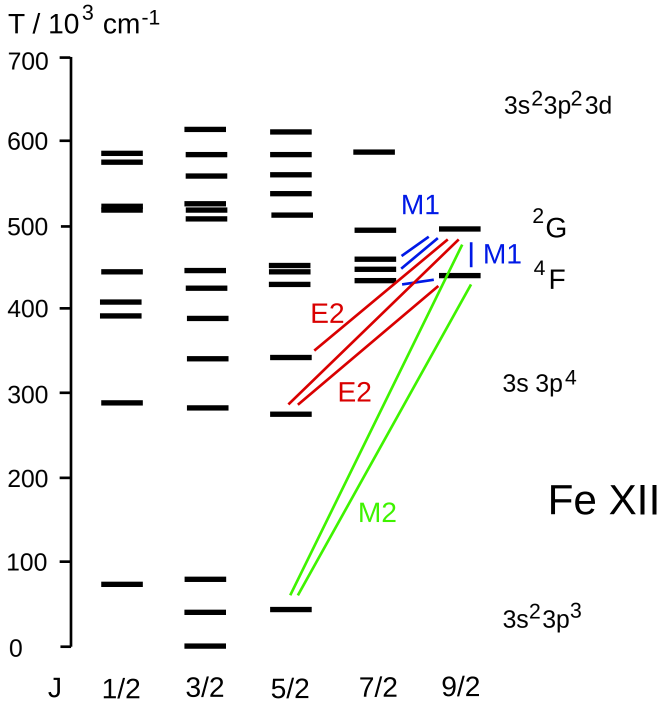

Figure 1. Fe XII levels up to the $3s^23p^23d$ levels. The E1-forbidden decays of the 3d levels lead to other levels in the same configuration (M1 transitions), or to specific high-J levels in the displaced ($3s3p^4$) and ground configurations.

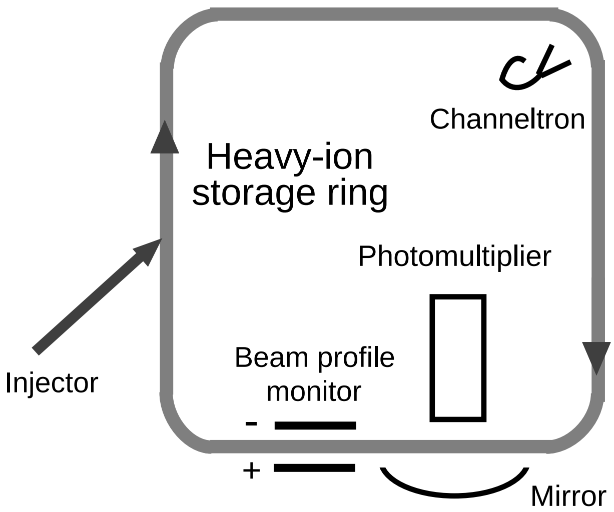

Figure 2. Experimental arrangement at the Heidelberg heavy-ion storage ring TSR. The ions enter the ring after excitation and charge state selection. Their photon emission is passively observed by either a windowless channeltron or by a UV photomultiplier. The stored ion beam current is monitored by a beam profile monitor that is also sensitive to EUV photons.

Table 1. Fe XII level lifetimes in the millisecond range and known or predicted principal decay channels (M1, E2, or M2). Wavelengths are approximate and based on observation, indirect evidence (calculated multiplet structure), or calculation (see text).

Upper level	λ(nm)^k	Lifetime τ (ms) Experiment	Theory
$3s^23p^3\ ^2D^o_{3/2}$	240.641	20.35 ± 1.24^h	18.9^a, 18.9^b, 5.0^c, 16.8^d, 16.0^e,
		18.0 ± 0.1^i	20.8^f, 18.4^g, 22.57^h $18.0/18.0^j$, 17.7^k
$3s^23p^3\ ^2D^o_{5/2}$	216.976	306 ± 10^i	324^a, 115^b, 326^c, 294^d, 313^e,
			544^f, 314^g $323/323^j$, 311^k
$3s^23p^3\ ^2P^o_{1/2}$	307.206, 356.6	4.38 ± 0.42^h	3.84^a, 3.84^b, 3.84^c, 3.64^d, 3.58^e,
		4.10 ± 0.12^i	4.05^f, 3.81^g $3.59/3.79^j$, 3.8^k
$3s^23p^3\ ^2P^o_{3/2}$	256.677, 290.470	1.85 ± 0.24^h	1.61^a, 1.61^b, 2.39^c, 1.55^d, 1.53^e,
		1.70 ± 0.08^i	1.67^f, 1.59^g $1.59/1.59^j$, 1.6^k
$3s^23p^2(^3P)3d\ ^4F_{9/2}$	25.187, 59.2600,1421.868	11 ± 1*	$11.6/9.2^j$, 9.7^k
$3s^23p^2(^1D)3d\ ^2G_{9/2}$	184.723, 163.484, 64.292 22.167	4 ± 1*	$4.00/4.27^j$, 4.03^k

a [16], b [17], c [18], d [19], e [20], f [22], g [21], h [33], i [29], j [23] (two approximations), k [8], * This work

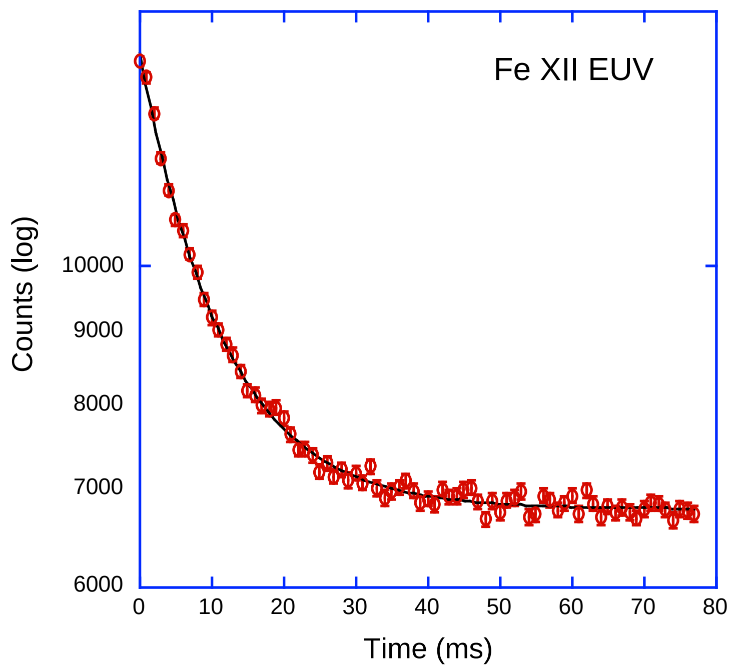

Figure 3. Decay curve of EUV light obtained at TSR with a windowless photomultiplier when Fe^{11+} ions were stored. The high base of the signal relates to residual gas excitation by the stored ions which is practically constant in this time interval. The decay curve on top relates to the decays of the $3s^23p^23d\ ^2G_{9/2}$ and $3s^23p^23d\ ^4F_{9/2}$ levels.